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Study of the dependence of Young's modulus of vertically aligned carbon nanotubes on their aspect ratio

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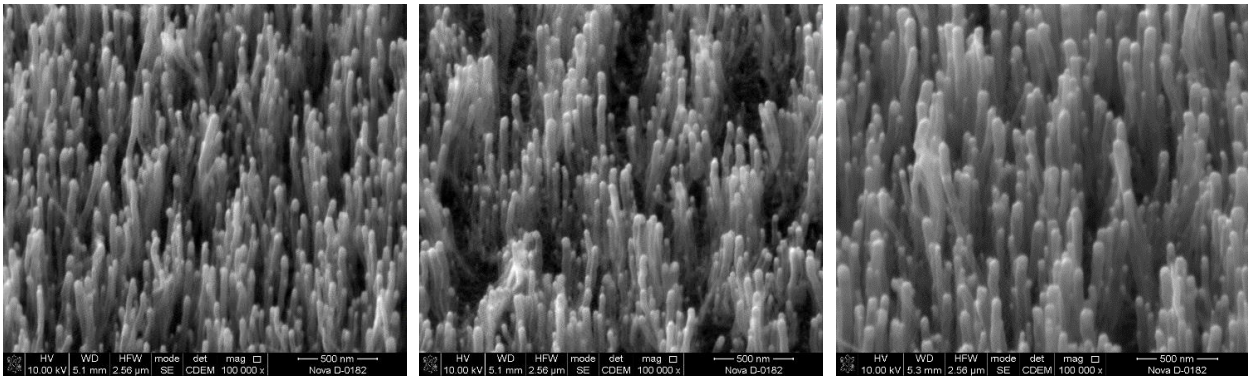
The rapid development of nanotechnology and the new opportunities in the field of nanoscale structures created a wide interest in the research of carbon nanotubes (CNTs) [1]. For the application of carbon nanotubes as an element base of electronics of new generation their mechanical parameters must be studied in detail. The Young's modulus is one of the main mechanical parameters of a CNT. However this parameter remains poorly understood due to the complexity of the experimental study of carbon nanotubes by using traditional methods (the direct tensile load, the pulse dynamic method, etc.) [2]. The aim of this work is to study the dependence of the Young's modulus of a vertically aligned CNTs on their aspect ratio using previously developed technique based on nanoindentation method.

As the experimental samples were used vertically aligned CNTs arrays grown by plasma enhanced chemical vapour deposition on a silicon wafer with a two-layer Ni/Ti structure on the surface. The arrays have the following values of diameter, height and density in array: No.1 – 43.8 nm, 0.65 μm, 82 μm^{-2}, No.2 – 35.6 nm, 1.21 μm, 72 μm^{-2}, No.3 – 51 nm, 0.69 μm, 69 μm^{-2}, respectively (Fig. 1).



No. 1 No. 2 No. 3

Figure 1. SEM images of experimental samples of vertically aligned CNT arrays.

The studies of the mechanical parameters of the CNT arrays were carried out at the Ntegra probe nanolaboratory using a scanning hardness nanotester integrated in it. The indenter was the diamond tree-sided Berkovich pyramid with the apex angle θ =70º between the edge and height.

The nanoindentation method is as follows: the indentor is pressed into the CNT array at a constant speed to a given depth; the dependence of the load values on the corresponding depth of the indentetion is established [2]. The nanoindentation process was carried out with the application of loads of 100 μN at 20 different points of the CNT array distant about 10 μm from each other. The obtained load curves are shown in Figure 2. The obtained dependence of the penetration depth on the indentation force is nonlinear and has two parts: the regions of elastic and inelastic interactions.

The peculiarity of the nanoindentation method of a vertically aligned CNT array is that nanotubes have the bending strain during the process. Therefore, the calculation of the effective bending stiffness of CNTs is made on the basis of the elastic region of load curves. The elastic region was from 0 to 250 nm for sample No. 1, from 0 to 210 nm for sample No. 2 and from 0 to 250 nm for sample No. 3. Then the Young's modulus is calculated on its basis.

The Young's modulus of carbon nanotubes are calculated by the formula [2]:

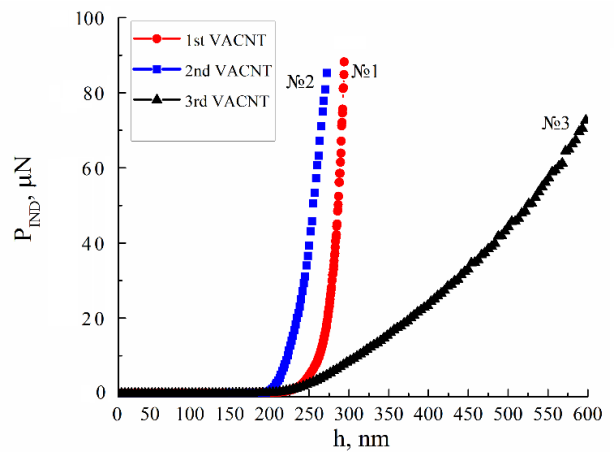


Figure 2. Load curves of vertically aligned carbon nanotubes for each sample.

$$E = \frac{64(P_{IN} - P_i)\cos\theta}{\pi i D^4 k^2},$$

where P_{IN} – indentation force, P_i – indentation force corresponding to the depth of the i-tube touch, i – amount of nanotubes interacting with the indenter at P_{IN}, D – a CNT diameter, $k = (P/(EI)_{eff})^{1/2}$ – the coefficient, $(EI)_{eff}$ – a effective bending stiffness of CNT.

The results of the studies showed that the Young's modulus is 1.15 TPa for sample No. 1 with aspect ratio 14.8, the Young's modulus is 1.29 TPa for sample No. 2 with aspect ratio 34, the Young's modulus is 0.59 TPa for sample No. 3 with aspect ratio 13.5 (Fig. 3). Thus the Young's modulus increases with increasing aspect ratio of CNTs. This is probably due to the fact that the number of defects in the structure of CNTs decreases with increasing their aspect ratio.

Thus, the dependence of Young's modulus of a vertically aligned carbon nanotubes on their aspect ratio is established experimentally. The obtained results are in good agreement with the literature data presented earlier [2,3]. The obtained results can be used to develop and creation of nanoelectronics devices based on vertically aligned CNTs in particular adhesion coatings and nonvolatile memory elements. The results were obtained using the equipment of REC and the Center for collective use "Nanotechnologies" of Southern Federal University.

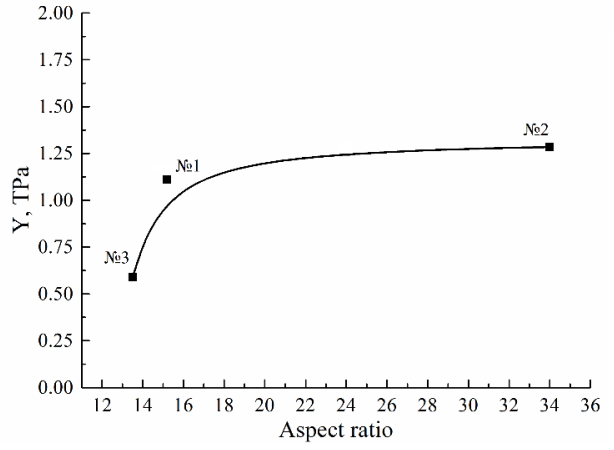


Figure 3. Dependence of the Young's modulus of the CNT on their aspect ratio.

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